Dynamic Bandwidth Allocation for NG-PONs With Channel Bonding

Aziza Zaouga, Amaro de Sousa, Monia Najjar, and Paulo Pereira Monteiro, *Senior Member, IEEE*

***Abstract*—Channel bonding is a recently proposed technique to provide higher aggregated line rates in NG-PONs by allowing ONUs to operate simultaneously in multiple wavelengths. On the other hand, the Dynamic Bandwidth Allocation (DBA) algorithm allocates to each ONU the grant time interval on each upstream frame that the ONU can use to transmit its data in the upstream direction. Channel bonding imposes a new challenge in the DBA algorithm as the grant time interval allocated to a ONU must be the same in all its channel-bonded wavelengths. In this work, we propose a new DBA algorithm for NG-PONs supporting data services which is a combination of a proportional fairness strategy and a max-min fairness strategy and guarantees the constraints imposed by channel bonding. We illustrate the merits of the new algorithm with two cases based on simulation. The results show that channel bonding can provide better QoS performance to data services even in cases where it is not strictly required.**

***Index Terms*—NG-PON, channel bonding, DBA.**

I. Introduction

RECENTLY, PON standardization groups (i.e., ITU-T and IEEE) are focusing on increasing the nominal line rate of PON systems beyond 10 Gbps in order to standardize 25G, 50G, 100G and beyond PON systems [1], [2]. In order to reach these goals, two main approaches are being combined: the implementation of wavelengths with line rates of 25 Gbps and the use of channel bonding to provide aggregated line rates of 50 Gbps and 100 Gbps [3]. The channel bonding mechanism consists on enabling an Optical Network Unit (ONU) to operate simultaneously on multiple wavelengths, achieving higher aggregated line rates to further accommodate the increase of customers and bandwidth demand [4].

Consider the illustration in Fig. 1 of a Next Generation - Passive Optical Network (NG-PON) with 4 wavelengths, each one with a line rate of 25 Gbps. A ONU can operate on a single wavelength (e.g., ONU #1 operating on wavelength λ_1 with a line rate of 25 Gbps) or on channel-bonded wavelengths (e.g., ONU #2 operating on all wavelengths with an aggregated line rate of 100 Gbps or ONU #n operating on wavelengths λ_3 and λ_4 with as aggregated line rate of 50 Gbps).

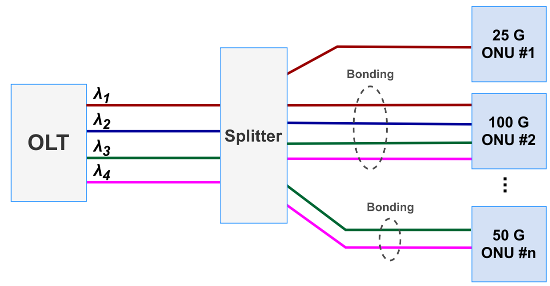


Fig. 1. Channel bonding in NG-PON systems.

ONUs operating on common wavelengths share the wavelengths' line rates in the upstream (US) direction. So, a Dynamic Bandwidth Allocation (DBA) mechanism is required to allocate the grant time intervals to ONUs that they can use to send their data in the US direction. In NG-PONs, a DBA decision is run in the Optical Line Terminal (OLT) every 125 μs (the duration of a NG-PON frame) to allocate the grant time interval to each ONU on the next US frame. The DBA decision is based on the current traffic need of each ONU, which can be determined either by the last report previously received from each ONU (indicating its last US queue occupation) or by estimation based on the past received reports.

The DBA mechanism is of key importance in NG-PONs as it affects its performance in terms of packet loss, packet delay and provided throughput. Several algorithms have been proposed for PON systems, including EPON and GPON families of standards [5], [6]. Concerning data services, the different proposed DBA schemes aim to provide a trade-off between fair bandwidth allocation among ONUs and network efficiency, following two main approaches: proportional fairness [7] or max-min fairness [8], [9].

The proposal in [7] uses proportional fairness by assigning weights proportional to the traffic need estimation of each ONU and, then, allocating the available bandwidth among all ONUs operation on the same wavelength (the single-wavelength DBA case) based in these weights. In [8], the single-wavelength DBA is addressed where the bandwidth is assigned to all ONUs operating on the same wavelength ordered in an increasing way by their traffic needs, none of the ONUs is assigned with more than it needs and the ONUs whose needs cannot be completely satisfied are assigned with the same bandwidth. In [9], a water-filling approach is used to provide max-min fairness in both single-wavelength and multi-wavelength DBAs (in the latter case, the ONUs are

Manuscript received September 20, 2021; revised November 3, 2021; accepted November 25, 2021. Date of publication December 6, 2021; date of current version February 12, 2022. This work is partially funded by FCT/MCTES and co-funded EU funds by the projects UIDB/50008/2020-UIDP/50008/2020 and POCI-01-0145-FEDER-016432. The associate editor coordinating the review of this letter and approving it for publication was G. Contestabile. *(Corresponding author: Aziza Zaouga.)*

Aziza Zaouga is with the Departamento de Electrónica, Telecomunicações e Informática, Instituto de Telecomunicações, Universidade de Aveiro, 3810-193 Aveiro, Portugal, and also with the Communications Systems Laboratory (SysCom), National Engineering School of Tunis (ENIT), University of Tunis El Manar (UTM), Tunis 1068, Tunisia (e-mail: aziza.zaouga@gmail.com).

Amaro de Sousa and Paulo Pereira Monteiro are with the Departamento de Electrónica, Telecomunicações e Informática, Instituto de Telecomunicações, Universidade de Aveiro, 3810-193 Aveiro, Portugal (e-mail: asou@ua.pt; paulo.monteiro@ua.pt).

Monia Najjar is with the Communication Systems Laboratory (SysCom), National Engineering School of Tunis (ENIT), University of Tunis El Manar (UTM), Tunis 1068, Tunisia (e-mail: monia.najar@isi.utm.tn).

Digital Object Identifier 10.1109/LCOMM.2021.3133101

assumed to be able to change their operating wavelength between frames).

Channel bonding imposes a new challenge in the DBA (not addressed in the previous proposals) as the grant time interval allocated to an ONU must be the same in all its channel-bonded wavelengths. Moreover, the required tuning time to change the operating wavelengths on ONUs is much longer than the frame duration of 125 μs [10] and, so, we consider that the wavelengths at which each ONU operates (including the channel-bonded wavelengths) are initially assigned and remain constant over time.

Consider again the example of Fig. 1 where ONU #1 and ONU #2 are both operating in wavelength λ_1. The grant time interval allocated to ONU #2 must be time disjoint with the grant time interval allocated to ONU #1 as the two ONUs cannot send data simultaneously in wavelength λ_1. In this case, the DBA decision cannot be made on a per wavelength basis and none of the previous proportional and max-min fairness approaches can be directly applied without proper adaptation. A recent DBA algorithm proposed in [11] considers channel bonding in NG-PONs to jointly support 5G fronthaul and data services. However, that work limits the scope of channel bonding assuming that all ONUs are operating on the same set of channel-bonded wavelengths and, in this case, channel bonding constraints do not need to be addressed.

Here, we propose a DBA algorithm for NG-PONs supporting data services compliant with the channel bonding constraints. It is a combination of the proportional and max-min fairness approaches and the DBA decision is only based on the last report previously received from each ONU (avoiding the complexity of the traffic estimation task). The new algorithm requires that the wavelengths initially assigned to the ONUs must allow the time granted to each ONU to be allocated on a single grant time interval within the US frame duration. We illustrate the merits of the proposed DBA algorithm with two cases based on simulation. In the simulation experiments, instead of considering Poisson traffic, we consider bursty traffic as it models more closely the traffic of data services. The simulation results will show that channel bonding can provide better Quality of Service (QoS) performance to data services even in cases where it is not strictly required.

The letter is organized as follows. Section II addresses the initial NG-PON wavelength assignment issue. Section III describes the proposed DBA algorithm. Section IV presents the simulation results together with their analysis and, finally, Section V presents the final concluding remarks.

II. Initial Wavelength Assignment

Consider a NG-PON system with a set N of ONUs (labelled as $n = 1, \ldots, |N|$) and a set W of wavelengths (labelled as $w = 1, \ldots, |W|$), each one with a line rate of C bits/second. Since each ONU operating in multiple wavelengths must be equipped with one transceiver per wavelength, a primary decision must be made by the PON operator on how many wavelengths must be assigned to each ONU (a decision usually based on a long-term prediction of the traffic demand required on each ONU). Consider T_n as the required number of wavelengths in ONU $n = 1, \ldots, |N|$ defined by the operator.

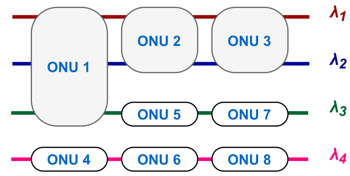


Fig. 2. First wavelength assignment example.

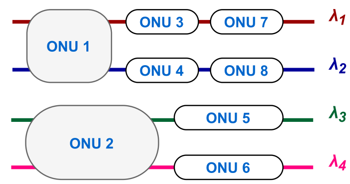


Fig. 3. Second wavelength assignment example (used in the simulation results as Configuration 2).

Then, the initial wavelength assignment is the task of selecting, among the set W of available wavelengths, the ones to be used by each ONU. The DBA algorithm (described in the next section) requires that, whatever time is granted to each ONU, it can always be allocated on a single grant time interval within the US frame duration. The simplest way to guarantee this requirement is as follows.

The assignment is done for each ONU n ordered by its T_n value in decreasing order and assigning consecutive wavelengths, starting from λ_1, to all ONUs requiring channel-bonded wavelengths (i.e., requiring more than one wavelength). Then, the ONUs requiring a single wavelength are assigned in round-robin among the wavelengths with less already assigned ONUs. Fig. 2 illustrates this case for $|W| = 4$ wavelengths and $|N| = 8$ ONUs where $T_n = \{3, 2, 2, 1, 1, 1, 1, 1\}$. ONUs 1, 2 and 3 are assigned with wavelengths up to λ_3, λ_2 and λ_2, respectively. Then, ONUs from 4 to 8 are assigned, one at a time, with the wavelength that has less number of previous assigned ONUs and, in case of multiple wavelengths in the same condition, in a round-robin fashion among them.

Fig. 2 illustrates a case where the grant time interval (the width of each box) is the same for all ONUs. In general, the time intervals granted by the DBA are different. Consider the example of ONU 1: whatever its grant time interval is, the remaining frame duration on any of its wavelengths (λ_1 to λ_3) is a single interval that can be freely assigned to the other ONUs operating on these wavelengths. The same property stands for the channel-bonded wavelengths of ONUs 2 and 3. Therefore, whatever grant time assigned to any ONU, it is always possible to allocate it on a single time interval.

There are also other possible ways. In the typical case of $|W| = 4$ wavelengths, if the number of wavelengths required by the ONUs is either 1 or 2, then, the set of wavelengths can be partitioned in 2 sets ($\lambda_1 - \lambda_2$ and $\lambda_3 - \lambda_4$) and the ONUs requiring 2 wavelengths can be assigned with one of the sets in a round robin way. Fig. 3 illustrates this case for $|N| = 8$ ONUs where $T_n = \{2, 2, 1, 1, 1, 1, 1, 1\}$.

III. DBA Algorithm

Table I presents all parameters used in the DBA algorithm description. In Table I, f_w representing the frame duration of

TABLE I
PARAMETERS

Parameters	Definition
f	Frame duration (f = 125 μs)
N	Set of ONUs, with ONU $n = 1...\|N\|$
W	Set of wavelengths, with wavelength $w = 1...\|W\|$
C	Capacity (i.e., line rate) of each wavelength (bits/sec)
T_n	No. of wavelengths of ONU n
W_n	Set of wavelengths used by ONU n, with $\|W_n\| = T_n$
N_w	Set of ONUs using wavelength w
g	Guard time duration (sec)
f_w	Frame duration of wavelength w without guard times
b_n	Request value of ONU n (in Bytes)
r_n	Request value of ONU n (in sec)
a_w	Remaining time of wavelength w
s_f	Starting time of the next US frame (sec)
t_n	Grant time duration assigned to ONU n (sec)
s_n	Starting time of grant time interval of ONU n (sec)
e_n	Ending time of grant time interval of ONU n (sec)

wavelength w available for granting is given by $f_w = f - |N_w| \times g - \sum_{n \in N_w} \tau_n$ where f is the total frame duration, N_w is the set of ONUs using wavelength w, g is the required guard time between grant time intervals and τ_n is the required transmission time of a request report on ONU n. Moreover, r_n representing the request value in seconds of ONU n is given by $r_n = \dfrac{8 \times b_n}{C \times |W_n|}$ where b_n is the queue occupation (in Bytes) reported by ONU n in the previous US frame and $C \times |W_n|$ is the total capacity of the wavelengths used by ONU n.

The proposed DBA algorithm is composed by Algorithm 1 that assigns a grant time to each ONU and Algorithm 2 that allocates the grant time interval (with the previous assigned grant times) to each ONU within the US frame duration. In Algorithm 1, the DBA first assigns grant times based on the ONU requests and uses proportional fairness among the ONUs whose requests cannot be completely satisfied. Then, since data services are highly bursty, a sudden traffic increase can happen in any ONU and, therefore, the remaining time on the different wavelengths is assigned (and added to the previous grant times) using max-min fairness.

Algorithm 1 starts by assigning a grant time t_n to each ONU n with its request r_n (lines 1–3) and by calculating the remaining time a_w on each wavelength w (lines 4–6). If all requests can be assigned (i.e., $argmin_{w \in W} a_w \geq 0$), proportional fairness is skipped (lines 7–15). Otherwise, the wavelength w' (i.e., the one with the highest negative value of a_w) is computed (line 8), the grant times t_n of the ONUs n using wavelength w' are reduced proportionally to their request values r_n so that all grant times fit in frame duration $f_{w'}$ (lines 9–11) and the remaining time a_w on each wavelength w is computed again (lines 12–14). This process is repeated until all assigned grant times fit in all wavelengths (line 7), i.e, all a_w values become non-negative.

In the max-min fairness part (lines 17–37), the algorithm first computes (lines 18–25) the set W' of wavelengths with remaining time (i.e., with $a_w > 0$) and the set N' of ONUs only operating on the wavelengths in W'. Then, for each wavelength w in W' (line 26), its remaining time a_w is split by all its ONUs n in N' and the values are stored in variables t_{nw} (lines 27–29). Then, the grant time t_n of each ONU n in N' is added with the minimum value among all its t_{nw} values (lines 31–33) and the remaining time on each wavelength w is calculated again (lines 34–36). This process is repeated until no remaining time can be added to any ONU (i.e., when $|N'| = 0$). Note that with channel bonding, the grant time assigned to ONU n is granted on all its wavelengths W_n. So, the remaining time of each wavelength is split by all its ONUs n with a weight inversely proportional to $|W_n|$ (line 28).

Algorithm 1 Assignment of Grant Times to ONUs

1: **for** $n \in N$ **do**
2: $\quad t_n = r_n$
3: **end for**
4: **for** $w \in W$ **do**
5: $\quad a_w = f_w - \sum_{n \in N_w} t_n$
6: **end for**
7: **while** $\min_{w \in W} a_w < 0$ **do**
8: $\quad w' = argmin_{w \in W} a_w$
9: $\quad$ **for** $n \in N_{w'}$ **do**
10: $\quad\quad t_n = \frac{r_n \times f_{w'}}{\sum_{i \in N_{w'}} r_i}$
11: $\quad$ **end for**
12: $\quad$ **for** $w \in W$ **do**
13: $\quad\quad a_w = f_w - \sum_{n \in N_w} t_n$
14: $\quad$ **end for**
15: **end while**
16: $W' = W$, $N' = N$
17: **while** $|N'| > 0$ **do**
18: $\quad$ **for** $w \in W'$ **do**
19: $\quad\quad$ **if** $a_w = 0$ **then**
20: $\quad\quad\quad W' = W' - \{w\}$
21: $\quad\quad\quad$ **for** $n \in N_w$ **do**
22: $\quad\quad\quad\quad N' = N' - \{n\}$
23: $\quad\quad\quad$ **end for**
24: $\quad\quad$ **end if**
25: $\quad$ **end for**
26: $\quad$ **for** $w \in W'$ **do**
27: $\quad\quad$ **for** $n \in \{N_w \cap N'\}$ **do**
28: $\quad\quad\quad t_{nw} = \frac{a_w \times \frac{1}{|W_n|}}{\sum_{i \in N_w \cap N_{w'}} \frac{1}{|W_i|}}$
29: $\quad\quad$ **end for**
30: $\quad$ **end for**
31: $\quad$ **for** $n \in N'$ **do**
32: $\quad\quad t_n = t_n + \min_{w \in W_n} t_{nw}$
33: $\quad$ **end for**
34: $\quad$ **for** $w \in W'$ **do**
35: $\quad\quad a_w = f_w - \sum_{n \in N_w} t_n$
36: $\quad$ **end for**
37: **end while**

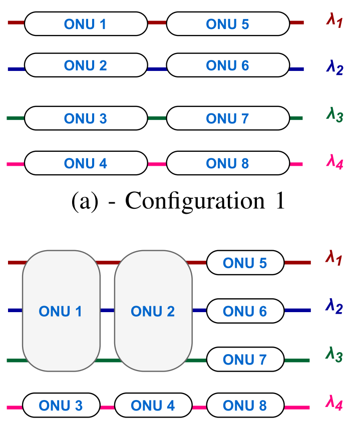
Finally, the allocation of grant time interval (i.e., its starting s_n and ending time instant t_n) of each ONU n is presented in Algorithm 2, where the for cycle (lines 4–10) considers the ONUs in a decreasing order of their T_n values.

IV. SIMULATIONS RESULTS

Consider a 100 Gbps NG-PON system with $W = 4$ wavelengths (of 25 Gbps each) and $N = 8$ ONUs whose distances from the OLT is 20 km. Consider the following 4 NG-PON system configurations:

Algorithm 2 Allocation of Grant Time Intervals to ONUs

for $w \in W$ **do**
  $Aux_w = s_f$
end for
for $n \in N$ **do**
  for $w \in W_n$ **do**
    $s_n = Aux_w$
    $e_n = s_n + t_n$
    $Aux_w = e_n + g$
  end for
end for



(a) - Configuration 1

(b) - Configuration 3

Fig. 4. Wavelength assignment configurations.

Configuration 1 – all ONUs are assigned with 1 wavelength (i.e., no channel bonding), with the assignment in Fig. 4(a);

Configuration 2 – ONUs 1 and 2 are assigned with 2 channel-bonded wavelengths each, and all other ONUs are assigned with 1 wavelength, with the assignment in Fig. 3;

Configuration 3 – ONUs 1 and 2 are assigned with 3 channel-bonded wavelengths each, and all other ONUs are assigned with 1 wavelength, with the assignment in Fig. 4(b);

Configuration H – all ONUs are operating on a single wavelength with a line rate of 100 Gbps; this configuration is currently not feasible and is used as reference since it allows full flexibility in the allocation of grant time intervals.

In all configurations, we consider a US packet queue on each ONU (required to store all incoming packets before the next grant time interval) of size 1.5 MBytes. This value is the queuing limit given by the NG-PON system capacity (100 Gbps) multiplied by the frame duration (125 μs) and divided by 8 (to turn the value into Bytes). Consider a given time period such that ONU $n = 1, \ldots, |N|$ has a number of active clients given by c_n. The data traffic of each active client in the US direction is modelled as follows:

- data is generated in sequences of random bursts, whose sizes are either between 64 and 10^3 Bytes (small bursts) with a probability of 80%, or between $10^3 + 1$ and 10^7 Bytes (long bursts) with a probability of 20% (all sizes of each burst type with equal probability);
- each burst is segmented in packets of 1500 Bytes, sent from the client to the ONU with a peak rate of 10 Gbps;

TABLE II
SIMULATION RESULTS OF SCENARIO 1

System configuration	2	3	H
Average US packet delay (μs)	135	134	148
Confidence interval (μs)	±1.21	±0.574	±0.637
Total US throughput (Gbps)	90.5	91	90.9
Confidence interval (Gbps)	±1.11	±0.89	±1.53
Average US packet loss (%)	0.45	0.032	0.216
Confidence interval (%)	±0.084	±0.017	±0.0382

- the time between the beginning of consecutive bursts is modelled with an exponential distribution with a burst rate that results in an average data rate of 500 Mbps.

We implemented in Matlab a simulator of the NG-PON system with the proposed DBA. In the simulations, we consider a DBA decision of 10 μsec, i.e., the DBA decision is run with the last request of each ONU received until 10 μsec before the time instant the decision is sent to all ONUs (simulations with different decision values up to 50 μsec show similar results).

In the next two subsections, we describe (and discuss) separately the simulation results obtained for two different data traffic scenarios. All simulation results were obtained with 20 runs to obtain the 95% confidence intervals, where each run simulates 5000 frames of the NG-PON system. Performance is evaluated in terms of average US packet delay, total US throughput and average US packet loss.

A. Scenario 1

In Scenario 1, we consider a number of active clients $c = \{80, 60, 9, 9, 9, 5, 5, 5\}$ for ONUs $N = \{1, 2, 3, 4, 5, 6, 7, 8\}$. Given that average data rate of each active client is 500 Mbps, the aggregated average throughput (in Gbps) at each ONU is $\{40, 30, 4.5, 4.5, 4.5, 2.5, 2.5, 2.5\}$ with a total average throughput of 91 Gbps (i.e., very close to the NG-PON capacity).

Since ONUs 1 and 2 are supporting an aggregated average throughput higher than 25 Gbps (i.e., 40 and 30 Gbps, respectively) and lower than 50 Gbps, this data traffic scenario can only be realized in practice if ONUs 1 and 2 are set with at least 2 channel-bonded wavelengths. So, we have simulated this scenario for Configurations 2, 3 and H with the results presented in Table II where, as can be observed, the confidence intervals are small enough so that we can draw conclusions.

Comparing the results of Configuration 2 with the reference Configuration H, Configuration 2 provides an average packet delay (135 μs) better than the reference one (148 μs) but a packet loss (0.45%) worse than the reference one (0.216%). Then, considering Configuration 3, the average packet delay (134 μs) is similar to the one in Configuration 2 and the average packet loss (0.032%) becomes much better than the ones of the other configurations (it represents a huge packet loss reduction). Finally, the total provided throughput is similar in all configurations, an expected result since the average packet loss values are all below 1%.

As already noted, the reference Configuration H has the advantage over the other configurations of allowing full flexibility to the DBA in the allocation of grant time intervals. Nevertheless, by supporting all ONUs in a single wavelength (of 100 Gbps), the DBA assigns (in the reference configuration)

TABLE III
SIMULATION RESULTS OF SCENARIO 2

System configuration	1	2	H
Average US packet delay (μs)	188	157	156
Confidence interval (μs)	± 2.68	± 2.32	± 1.04
Total US throughput (Gbps)	87.2	89.3	90.6
Confidence interval (Gbps)	± 1.02	± 1.04	± 1.14
Average US packet loss (%)	2.97	0.767	0.121
Confidence interval (%)	± 0.241	± 0.127	± 0.0364

grant time intervals much shorter (for the same request values from ONUs) than the ones in the other configurations. So, the elapsed time from the end of a grant time interval to the beginning of the next one is larger, penalising the average time the incoming packets wait for their transmission opportunity. In the results of Table II, this factor is clearly the reason that justifies the better QoS (in terms of packet delay) of both Configurations 2 and 3 when compared with the reference.

Finally, Configuration 3 (not strictly required for this data traffic scenario) improves the QoS performance in terms of packet loss (when compared with Configuration 2) because, for each ONU pair, the ratio of the number of wavelengths used by each ONU is closer to the ratio of the average throughput supported by each ONU in Configuration 3.

B. Scenario 2

In Scenario 2, we consider a number of active clients on each ONU given by $c = \{48, 44, 20, 20, 20, 10, 10, 10\}$. The resulting aggregated average throughput (in Gbps) at each ONU is $\{24, 22, 10, 10, 10, 5, 5, 5\}$ with again a total average throughput of 91 Gbps. Scenario 2 is more homogeneous than Scenario 1 as the aggregated throughput values at each ONU are closer, on average, to the average throughput per ONU.

In this scenario, all ONUs are supporting an aggregated average throughput not higher than 25 Gbps and, therefore, channe bonding is not strictly required. So, we have simulated this scenario for Configurations 1, 2 and H, whose results are presented in Table III.

Comparing the results of Configuration 1 with the reference Configuration H, Configuration 1 provides worst QoS both in terms of packet delay and packet loss. Then, considering Configuration 2, both QoS parameters are significantly improved (when compared with Configuration 1) and become much closer to the reference ones. Since now packet loss values are higher than in the previous Scenario 1, there are observable improvements in terms of total provided throughput from Configuration 1 to 2 and to the reference one.

Two main conclusions can be drawn from these results. Firstly, the reference Configuration H provides the best QoS, which means that in this data traffic scenario the positive impact of the full flexibility provided to the DBA is higher than the negative impact of the larger times the incoming packets need to wait for their transmission opportunities. Secondly, and more importantly, although not strictly required, the use of channel bonding in ONUs 1 and 2 (providing higher capacities to the ONUs supporting higher aggregated average throughput values) has improved all QoS values when compared with the case of not using channel bonding.

V. CONCLUDING REMARKS

Channel bonding is a recently proposed technique to provide higher aggregated line rates in NG-PONs, which imposes a new challenge in the DBA algorithm not addressed in previous DBA proposals. In this work, we have proposed a DBA algorithm for NG-PONs supporting data services which guarantees the constraints imposed by channel bonding. Moreover, the DBA decision is only based on the last report previously received from each ONU avoiding the complexity of the traffic estimation task used in previous approaches.

We have illustrated the merits of the proposed DBA algorithm with two data traffic scenarios assessing by simulation the provided QoS to data services. The results indicate that, by provisioning higher capacities (i.e., with more wavelengths) to the ONUs supporting more data traffic, the proposed DBA provides better QoS performance to data services with channel bonding even in cases where it is not strictly required.

In general, one should expect that the QoS performance of the proposed DBA strongly depends on the long-term traffic demand prediction used to decide how many wavelengths are initially assigned to each ONU. If the actual traffic demands supported by the ONUs suffer a strong deviation from the initially predicted values, then the capacities provided to the different ONUs become not proportional to the data traffic supported by them and the provided QoS becomes degraded.

REFERENCES

[1] *IEEE Standard for Ethernet Amendment 9: Physical Layer Specifications and Management Parameters for 25 Gb/s and 50 Gb/s Passive Optical Networks*, Standard 802.3ca-2020, 2020.

[2] D. Zhang, D. Liu, X. Wu, and D. Nesset, "Progress of ITU-T higher speed passive optical network (50G-PON) standardization," *J. Opt. Commun. Netw.*, vol. 12, no. 10, pp. D99–D108, 2020.

[3] F. J. Effenberger, "Industrial trends and roadmap of access," *J. Lightw. Technol.*, vol. 35, no. 5, pp. 1142–1146, Mar. 1, 2017.

[4] L. Zhang, Y. Luo, N. Anwari, B. Gao, X. Liu, and F. Effenberger, "Enhancing next generation passive optical network stage 2 (NG-PON2) with channel bonding," in *Proc. Int. Conf. Netw., Archit., Storage (NAS)*, Aug. 2017, pp. 1–6.

[5] J. Y. Lee, I. S. Hwang, A. Nikoukar, and A. T. Liem, "Comprehensive performance assessment of bipartition upstream bandwidth assignment schemes in GPON," *J. Opt. Commun. Netw.*, vol. 5, no. 11, pp. 1285–1295, 2013.

[6] P. Sikora, T. Horvath, P. Munster, and V. Oujezsky, "Efficiency tests of DBA algorithms in XG-PON," *Electronics*, vol. 8, no. 7, p. 762, Jul. 2019.

[7] P. Sarigiannidis, G. Papadimitriou, P. Nicopolitidis, E. Varvarigos, M. Louta, and V. Kakali, "IFAISTOS: A fair and flexible resource allocation policy for next-generation passive optical networks," in *Proc. 6th Int. Congr. Ultra Modern Telecommun. Control Syst. Workshops (ICUMT)*, Oct. 2014, pp. 7–14.

[8] I. Gravalos, K. Yiannopoulos, G. Papadimitriou, and E. A. Varvarigos, "A modified max-min fair dynamic bandwidth allocation algorithm for XG-PONs," in *Proc. 19th Eur. Conf. Netw. Opt. Commun. (NOC)*, Jun. 2014, pp. 57–62.

[9] J. Zhang and N. Ansari, "Dynamic time allocation and wavelength assignment in next generation multi-rate multi-wavelength passive optical networks," in *Proc. IEEE Int. Conf. Commun.*, May 2010, pp. 1–5.

[10] A. Dixit, B. Lannoo, D. Colle, M. Pickavet, and P. Demeester, "Dynamic bandwidth allocation with optimal wavelength switching in TWDM-PONs," in *Proc. 15th Int. Conf. Transparent Opt. Netw. (ICTON)*, Jun. 2013, pp. 1–4.

[11] A. Zaouga, A. F. de Sousa, M. Najjar, and P. P. Monteiro, "Self-adjusting DBA algorithm for next generation PONs (NG-PONs) to support 5G fronthaul and data services," *J. Lightw. Technol.*, vol. 39, no. 7, pp. 1913–1924, Apr. 1, 2021.